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The Nature of Loop-Top Sources in Solar X-ray Flares

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Abstract:

Bright, compact loop-top sources or kernels are a conspicuous feature of soft X-ray flares as imaged by the SXT instrument on the Japanese solar mission *Yohkoh*, and their nature has been widely discussed. We have done a detailed comparison of the observations from the hard and soft X-ray imaging instruments (HXT and SXT) as well as the Bragg Crystal Spectometer (BCS) on *Yohkoh* for some 36 flares. We find evidence that the loop-top sources in these flares are highly non-isothermal, with temperature ranging from ~ 10 MK (as seen by SXT) to ~ 20 MK or more (as deduced from line ratios in the BCS range and the presence of gradually varying emission in the HXT 14–23 keV energy band). The SXT temperature maps (formed from the ratio of emission through two different filters) show that the temperature distribution within the loop-top source is uniform. We argue that the most plausible model to explain this is one in which the loop-top source is made up of highly tangled magnetic field lines, where current sheets continually form, supplying energy to the region. Both freshly heated plasma (~ 20 MK) and cooled plasma (~ 10 MK) co-exist in the same region. A calculation of the energy balance of the loop-top region suggests that the heating is not uniform within the region but rather is at a maximum near its edge. This may be explained by the reconnection of the tangled field with the field of the loop legs, which has a simple geometry.

1. Introduction

One of the outstanding discoveries made by the Japanese *Yohkoh* solar flare mission has been bright emission sources (also known as kernels or knots) at or near the tops of soft X-ray flaring loops (Feldman et al. 1994; Doschek & Feldman 1996). They have been imaged with the Soft X-ray Telescope (SXT) aboard *Yohkoh* (Tsuneta et al. 1991). For short-lived flares (i.e., lasting a few minutes), the source diameters are ≤ 2000 km with heights of order $10,000$ km high, but for long-duration (several hours) flares, their diameters are $\sim 10,000$ km with heights $> 50,000$ km. As the X-ray emission is optically thin, some sources may not be real but could in fact be the locations where two or more loops intersect, but the reality of most loop-top sources is undeniable, especially for comparatively simple flares.

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The various filters that can be deployed in SXT enable estimates to be made of electron temperatures $T_{\rm e}$, though more reliable values can be obtained spectroscopically using emission lines that are viewed by the Bragg Crystal Spectrometer (BCS) on *Yohkoh* (Culhane et al. 1991). The BCS is, however, an uncollimated spectrometer without spatial resolution, so it is not clear without other information whether the BCS emission is from the loop-top source. Khan et al. (1995) have established from successive flares in an active region rotating over the Sun's west limb that the BCS emission does in fact come from the loop-top source. It is evident, from the initial stages of nearly all flares, that nonthermal velocities are present, with values up to several hundred km $\rm s^{-1}$.

Two of us (Jakimiec & Fludra 1991) have investigated the heating of flare plasma and how it is maintained at temperatures of more than 10 MK (1 MK $= 10^6$ K) when calculations would suggest that thermal conduction to the comparatively cool chromosphere ($\sim 10^4$ K) would be very rapid. They suggested that there must be a high degree of MHD turbulence in a small region of energy release in the flare. Outside of these regions, along the legs of loops, the field line geometry was suggested to be simple.

There are several *Yohkoh* observations made since that work which appear to confirm this picture of solar flares. Here we discuss some observations which we have analyzed and which support the idea of the loop-top source having a tangled field geometry.

2. Observations

2.1. Instruments

The Japanese solar flare mission *Yohkoh* was launched on August 30, 1991 and continues to operate successfully at the time of writing (August 1997). The SXT is a grazing-incidence telescope sensitive to 3–50 Å X-rays, with a CCD detector and filters to provide wavelength discrimination. The filters sensitive to the highest energies, hence most suitable for flares, are a beryllium 119 μm (Be119) filter and a 11.6 μm Al (Al12) filter. Full-Sun images are formed continuously by the SXT, but when a flare occurs partial-frame images with fast time cadence are made so that the rapidly changing flare morphology can be followed. The BCS views X-ray lines of He-like Fe, Ca, and S and neighbouring dielectronic satellite lines from which it is possible to deduce $T_{\rm e}$ and emission measure $\langle N_{\rm e}^2 V\rangle$ ($N_{\rm e}$ = electron density, V = emitting volume). The Fe XXV lines are at ~ 1.85 Å, the Ca XIX lines are at ~ 3.18 Å, and the S XV lines are at ~ 5.04 Å. We also made use of data from the Hard X-ray Telescope (HXT, see Kosugi et al. 1991) which is a Fourier-synthesis imager measuring spatially modulated intensities from 64 independent subcollimators. Images are constructed from the data by the maximum entropy method or other procedures. The four energy bands cover the range 14–93 keV.

In our analysis of the observations, we used a standard IDL software package that is described by Morrison (1994).

2.2. Flare Selection

Pike et al. (1996) studied 75 flares observed with the BCS between 1991 and 1993 which have detectable Fe XXVI line emission. Fe XXV and Fe XXVI spectra were analyzed to derive temperatures $T_{\rm e}$(BCS) and emission measures ε(BCS) for short time intervals near flare maximum, but avoiding periods near the flare onset when X-ray line profiles are generally highly broadened.

To investigate any relation of the BCS Fe XXV temperatures and emission meaures to the SXT emission, we first defined the soft X-ray kernels in the SXT Be119 filter images at flare maximum as the emission within areas outlined by the isophote that is 50% of the brightest pixel, generally near the loop top. Temperatures $T_{\rm e}$(SXT) and emission measures ε(SXT) of the total radiaton within the kernel area were then found from the ratio of intensities in the Be119 and Al12 filters. This was done for the same time interval over which the BCS observations were made. Data from SXT were not always available for exactly the time intervals in the Pike et al. work, this being the main reason why only some (36) of the 75 flares were selected and analyzed. We obtained flare coordinates from the corresponding Hα flare. In general, the temperatures of the flare kernels are systematically lower, and the emission measures higher, than those obtained from the BCS Fe XXV spectra.

2.3. Comparison of BCS Data and the SXT Data

We found no appreciable correlation of flare loop-top temperatures from SXT with those derived from the BCS Fe XXV spectra over the limited range of each. However, a plot of emission measures derived from the SXT and BCS data (Fig. 1) shows a very good correlation, with almost all points falling within a factor 2 of the least-squares line (also shown). This plot includes flares at or off the solar limb with loop footpoints occulted, but such points lie near the least-squares line, showing that the loop-top source dominates the BCS Fe XXV emission. This near-proportional relation between the emission measures indicates the hotter ($T_{\rm e} \sim 20$ MK) and cooler ($T_{\rm e} \simeq 10$ MK) plasmas co-exist within the loop-top sources, suggesting a close physical relation between them.

The SXT Be119 and Al12 filter responses are rather weakly dependent on $T_{\rm e}$ and it is in principle possible for high-temperature (~ 20 MK) material to have a significant effect. We investigated this and found that in fact the emission measure of a high-temperature component would have to be a significant fraction (more than about 0.6) of the emission measure of a component at, say, $T_{\rm e} =$ 10 MK for the derived SXT temperature to be affected. This was generally not the case for the flares studied.

We investigated the spatial distribution of temperature and emission measure from SXT images. We found that the SXT temperature is very uniform – a value of 10.5 ± 1 MK approximately – over the kernel region. Temperatures in the loop legs generally have somewhat lower values. We note that there are instrumental effects (e.g., Siarkowski et al. 1996) leading to spuriously high temperatures along the edges of the loop-top source emission areas.

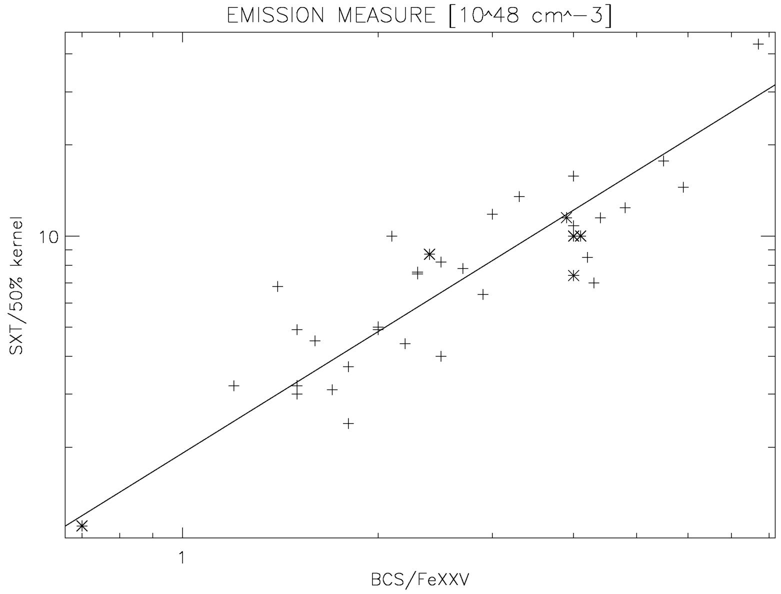

Figure 1. Correlation between the emission measure obtained for the SXT flare kernels and derived from BCS Fe XXV spectra for events from Table 1. A typical relative error is several percent. A linear fit to the data is shown as a continuous line.

2.4. Comparison Between Soft and Hard X-Ray Flare Images

The lowest energy (14–23 keV) band (*L*) of the HXT is sensitive to both non-thermal X-ray emission and very hot (∼ 20 MK) plasma emission, so outside of the flare impulsive stage HXT images in this channel give useful information about the distribution of hot plasma. For comparison with SXT images, an accurate co-alignment is important, and we achieved this with the data given by Masuda (1994). Like the result obtained by Masuda (1994), we found a close spatial relation between the thermal emission seen with the HXT *L* channel and the SXT emission, supporting the conclusion that the loop-top source contains both hot ($>\sim$ 20 MK) and cooler (∼ 10 MK) plasma in its volume. We illustrate the case for the flare of December 28, 1991, at various stages in its development (Fig. 2).

This relation is further supported by one between Fe XXV line emission as seen with the BCS instrument and the HXT *L*-channel photon counting rate (Fig. 3), where a linear dependence is indicated.

3. A Turbulent Magnetic Field Model for the Flare Kernel

The longevity of bright and apparently hot sources in X-ray flare images is surprising in view of the high thermal conductivity along magnetic field lines which are widely presumed to make up the loop-like geometry of X-ray flares (e.g., Kopp & Pneuman 1976). There are at least three considerations that lead us to doubt the existence of simple magnetic field geometries. First, the SXT temperature distribution is very uniform over the region of the loop-top source. Secondly, apparently high ($\geq$ 20 MK) temperatures co-exist in the loop-top

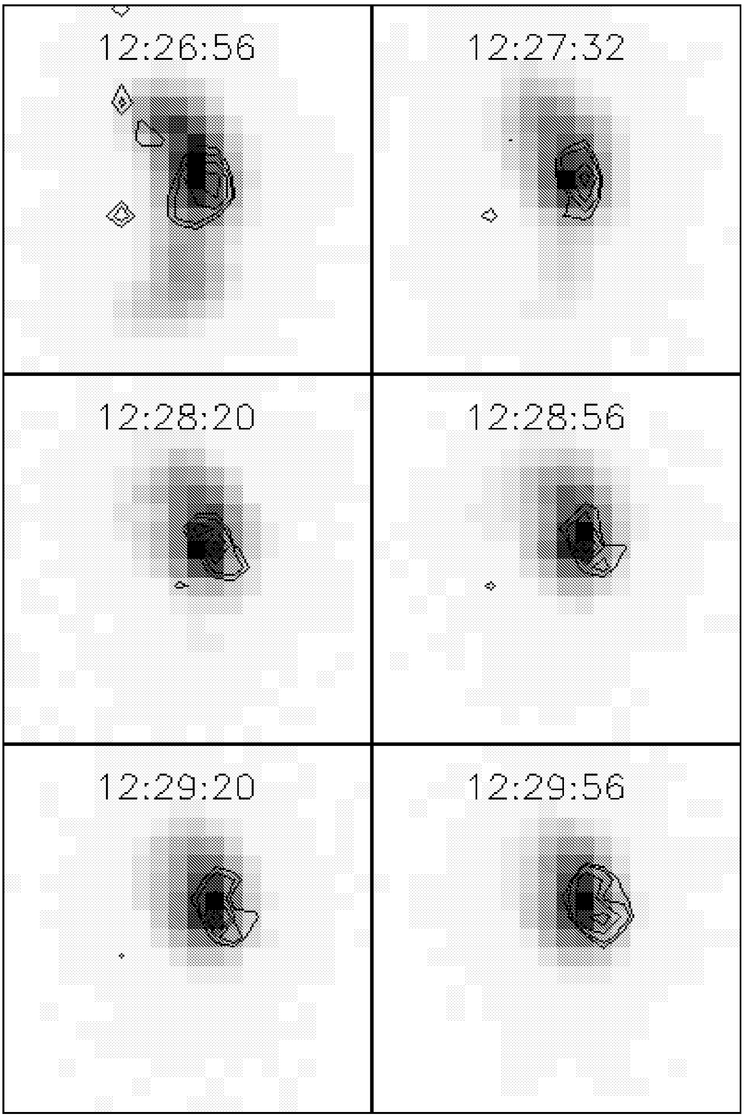

Figure 2. A mosaic of six SXT/Be119 images illustrating the evolution of the 28 December 1991 flare. Each image consists of 20 × 20 2.45 arc sec pixels and has its own scale of brightness based on the brightest pixel. North is at the top, east to the left. HXT(L) images are overplotted as contours, with levels equal to 78.4, 39.2, 19.6 and 11.8 % of the maximum intensity for each HXT image.

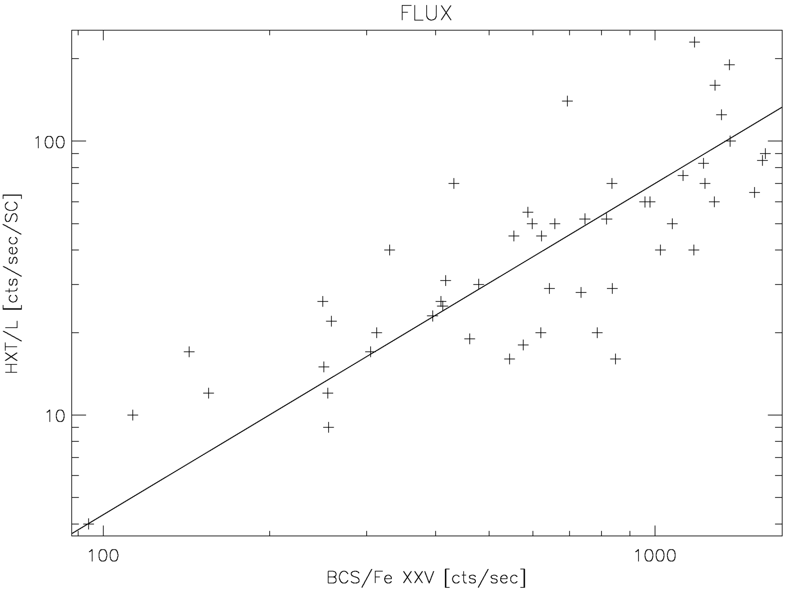

Figure 3. Correlation between the Fe XXV line emission (BCS) and the HXT intensities for the investigated flares. A linear fit to the data is shown as a continuous line. The statistical errors for both HXT and BCS are very small, though there may be a systematic error through intensity calibration uncertainties.

source with much lower temperatures ($\sim$ 10 MK); and finally the creation of a hot source at a particular location along the loop length is difficult to achieve in view of the extremely high thermal conductivity along the field lines if they have a simple geometry (the classical or Spitzer-Härm value being a strong function of $T_{\rm e}$, viz. $\sim 10^{-6}T^{5/2}$ cgs units).

We have considered a tangled field geometry for the loop-top source as this answers a number of puzzles and agrees with observations much more satisfactorily. Thus, in a model like that of Jakimiec & Fludra (1991), the field lines are so tangled that many transient, turbulent current sheets are formed. Fig. 4 shows the possible field line geometry in this picture which we propose here. Not all field lines in the loop-top region are simply connected to the field lines of the loop legs. Hence, heat flows only along some field lines. The thermal conductivity of plasma held to field lines with complex geometry will be significantly reduced if the coherence length of the field is much less than the mean free path of electrons travelling along the field lines (see, e.g., Sarazin 1986).

The theory of the energy balance will be developed in more detail in a later publication, but meanwhile we will briefly state what we think are the chief heating and cooling terms in the loop-top region. Let E_H be the heating rate per unit volume and E_R the radiative cooling rate per unit volume. Then $\mathbf{F}$, the thermal energy flux, is

$$\nabla . \mathbf{F} = E_H - E_R. \tag{1}$$

If we take the main energy transport mechanism to be by turbulence, with conductivity playing only a small rôle, we have for the energy flux

$$| \mathbf{F} | = -\kappa_t dT/dr \tag{2}$$

where dT/dr is the temperature gradient and κ_t is the coefficient of energy transport by turbulence, given by

$$\kappa_t = \rho c_p \bar{v} l/2 \tag{3}$$

with ρ the density, c_p the specific heat of the plasma at constant pressure, l the mixing length, and $\bar{v}$ the mean velocity of the turbulent elements. If we take the heating to be homogeneous, or $E_H =$ a constant, we may derive

$$\frac{dT}{dr} = -\frac{1}{3}\frac{E_H - E_R}{\kappa_t} r \tag{4}$$

and hence

$$T(r) = T_0 - \Delta T (r/R)^2, \tag{5}$$

where $\Delta T = (1/6)([E_H - E_R]/\kappa_t)R^2$, T_0 is the temperature at the centre of the kernel, and R is the kernel radius. This means that in the case of homogeneous heating there should be a maximum of the temperature at the centre of a kernel and a continuous decrease of the temperature towards the edge. Since we do not see a temperature maximum in the SXT maps, we conclude that the heating is not homogeneous, rather it is enhanced near the loop-top region's edge. Specifically, $E_H = E_R$ for a region inside a certain radial distance, and $E_H - E_R =$ a constant outside of this distance.

This agrees with what one might expect, since the tangled field of the loop-top region would interact with a field of simpler geometry, with the formation of current sheets.

4. Summary and Conclusions

Our investigation of loop-top sources evident in soft X-ray images of solar flares shows that a plausible explanation for their longevity and geometry consists of a region with tangled field geometry at the loop top. The field in this picture is so tangled that transient current sheets form, with hot ($\sim$ 20 MK) and cooler ($\sim$ 10 MK) plasma coexisting within the region, as our analysis and previous works show is the case. If we take the chief heat energy transport mechanism to be by turbulence, the heating function must be enhanced towards the edge of a loop-top region to explain the observational fact that the temperature as estimated by the *Yohkoh* SXT instrument is uniform within the region.

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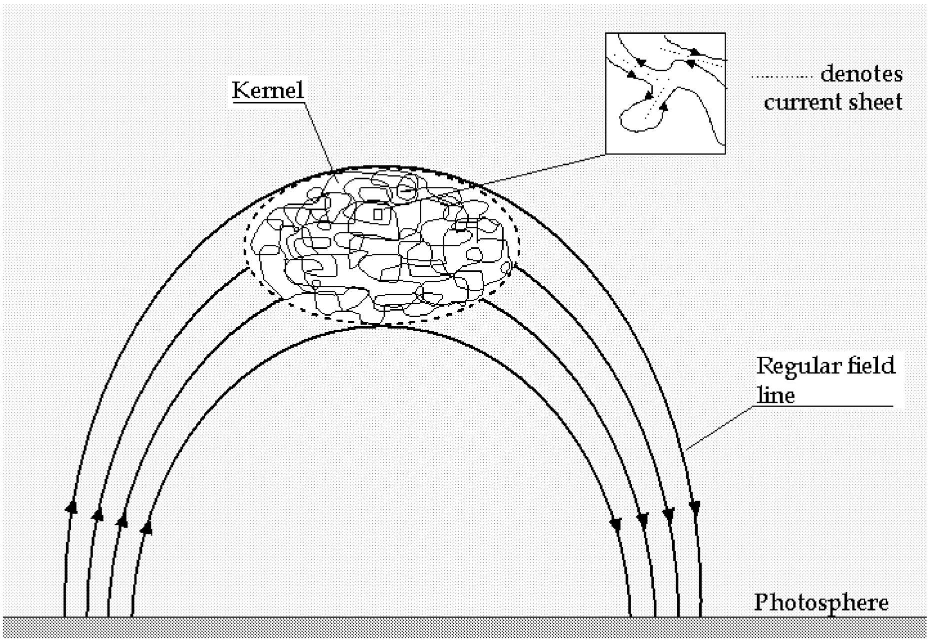

Figure 4. Model of the turbulent flare kernel as discussed in the text. The magnetic field lines have a simple geometry along the loop legs but are tangled in the kernel. Inset shows enlarged picture of reconnecting field lines and current sheets.

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